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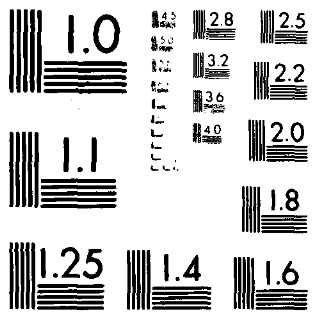

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CALCULATION OF GROUND SHOCK MOTION PRODUCED BY NEAR SURFACE AIRBURST EXPLOSIONS USING CAGNIARD ELASTIC PROPAGATION THEORY.

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JAMES R. BRITT, MR.
U.S. Army Engineer Waterways Experiment Station
Vicksburg, Mississippi 39180

1. INTRODUCTION

This paper describes a study which used elastic wave propagation theory to predict and analyze ground motions produced by near surface airburst explosions; the air-earth environment was modeled as three homogeneous elastic layers - air, soil and rock - separated by plane parallel boundaries as illustrated in Figure 1. The explosive source is located on the axis of symmetry. The air is treated as an elastic fluid, while the soil and rock are treated as elastic solids. Elastic material parameters that characterize the wave propagation are the compressional wave (P wave) speeds C_{pi}, the shear wave (S wave) speeds C_{si}, and the densities ρ_i where i = 1, 2, and 3 for the air, soil, and rock, respectively.

The exact closed form integral solutions of Cagniard (1) for the reflection and refraction of spherical waves in elastic solids were adapted and extended to model the ground shock propagation in a layered earth. In this formulation the particle motion is obtained as a sum of components propagated along rays or paths (such as shown in Figure 1) associated with distinct P and S wave arrivals. Calculations using the Cagniard procedure were used previously successfully by the author to predict the reflection of underwater explosion shock waves from the ocean bottom. (See References (2)-(5).) The theoretical analysis and computer code development for the ground shock calculations were extensions of the bottom reflection study. The details of the theoretical model and the computer code used in the elastic ground motion calculation are not presented but will be given in a forthcoming report (6). In addition, References (2)-(5) and (7)-(9)

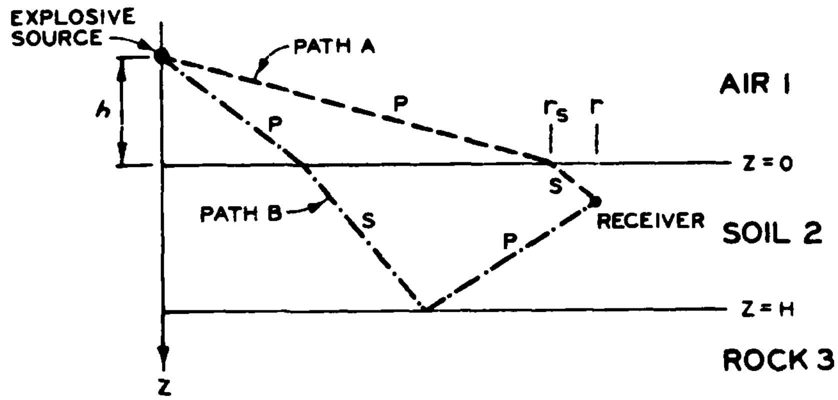


Figure 1. Model for airburst explosions over layered earth media.

provide background information and some other recent applications of the Cagniard elastic propagation theory.

2. MODELING THE AIRBLAST

The airblast pressure produced by an explosion attenuates with radial distance R from the source more like $1/R^2$ for pressure levels 10 to 100 psi than the spherical elastic $1/R$ decay rate. The blast propagation rate decreases with range instead of the constant speed C_{p1} . In addition, the pressure-time waveform changes in shape with range. Thus, the airblast cannot be directly modeled elastically but must be approximated by either (a) linearizing around a particular range related to the time of dominant motion or (b) by simulating the pressure amplitude and arrival time by a distribution of sources. The simpler linearization approach was used in this study. Several procedures were investigated, but linearization around the directly transmitted shear wave (path A of Figure 1) produced the best agreement with measured waveforms for materials ranging from weak soils to hard rocks.

A

The airblast was approximated as follows. The directly transmitted shear wave path A of Figure 1 was determined by iterating for the range r_s at which the ray enters the soil. An empirical formula was used to calculate the airblast arrival time t_a for an initial value of r_s. An average P wave speed C_{p1} was computed from

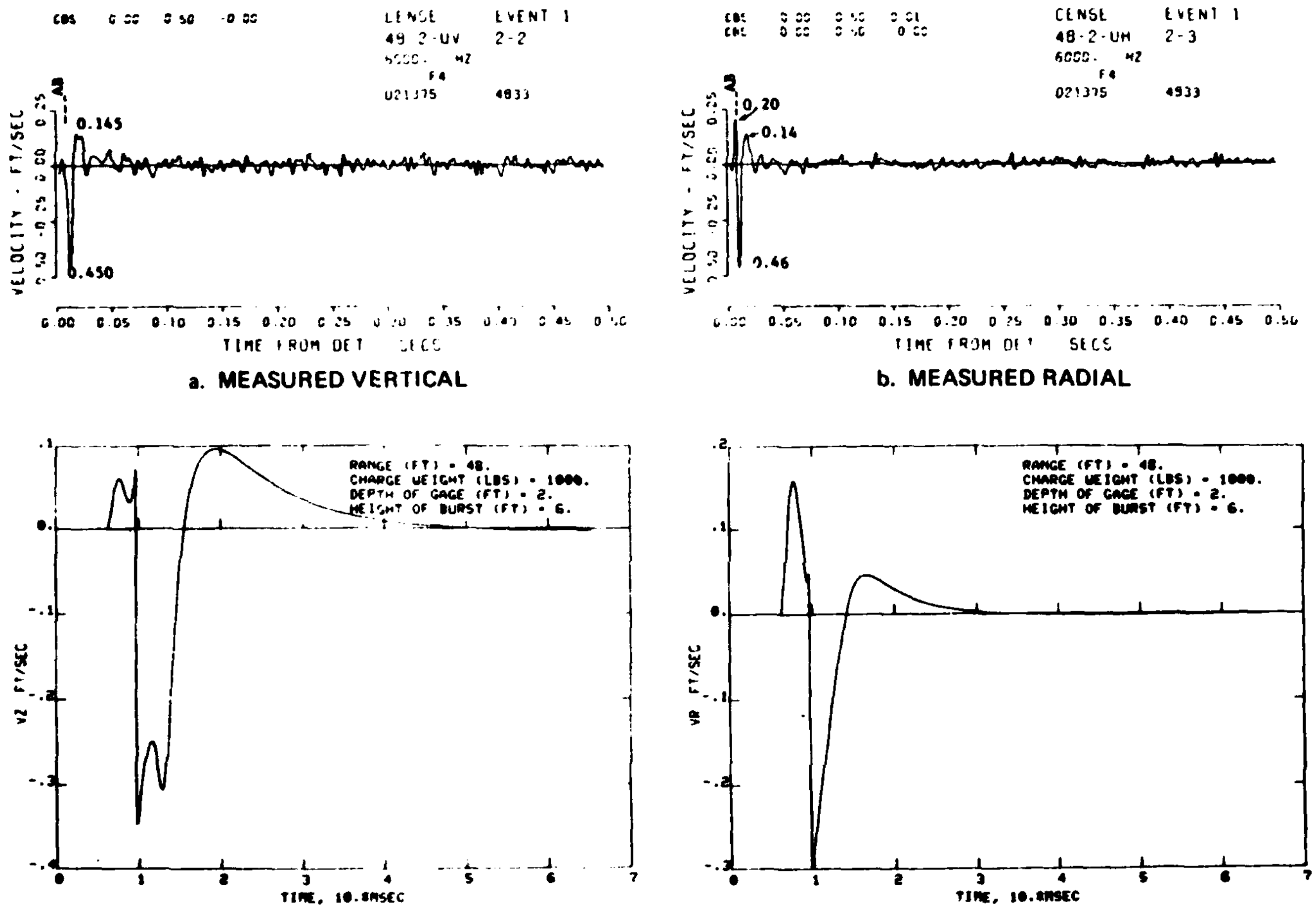
$$C_{p1} = (h^2 + r_s^2)/t_a$$

Then C_{p1} was substituted into the equation for Snell's Law of acoustics to obtain a new estimate for r_s. This process continued until the initial and final values of r_s were within an acceptable tolerance. The point source amplitude and pulse shape were then chosen using empirical formulae so that the airblast pressure was matched at the point $(r_s, 0)$.

3. COMPARISON OF CALCULATED AND MEASURED PARTICLE VELOCITY WAVEFORMS

Calculations were performed for the three CENSE (Coupling Efficiency of Near Surface Explosions) explosive field test series. (See References (10) and (11).) These tests were chosen because they provide a variety of site characteristics which were relatively well controlled. The test beds were either effectively homogeneous or had layering suitable for the two-layer model. In addition, each of the series had near surface airburst explosions for which particle velocity or acceleration was measured in the upper layer for a variety of ranges from the explosions.

CENSE 1 consisted of a series of 1000-lb spheres of nitromethane detonated over a massive Kayenta sandstone formation. These events provide data for checking the calculations for motion in a strong, homogeneous material which behaves elastically for stress levels of hundreds of psi. The surface rock was thick enough that three layers were not needed for the computations. Figure 2 compares the theoretical and measured vertical and radial velocity components. Vertical velocity is positive for upward motion and radial velocity is positive for outward motion. Note that the experimental and theoretical curves are plotted on different scales and that the calculation represents only part of the measured curve. The material properties used for this calculation were ρ_1 = 0.0012 gm/cm^3 , C_{p2} = 9 ft/msec , C_{s2} = 4 ft/msec , and ρ_2 = 2.4 gm/cm^3 . Event 1, shown in the figure, was detonated with its charge center 6 ft above the rock. Measurements were made with velocity gages (having a nominal 600-Hz frequency response) placed 2 ft below the rock surface. The airblast peak



a. MEASURED VERTICAL

b. MEASURED RADIAL

c. THEORETICAL VERTICAL

d. THEORETICAL RADIAL

Figure 2. Comparison of particle velocity calculations with CENSE 1 measurements at 48-ft range.

pressure above the gages was measured at 51 psi at the 48-ft range. Other calculations not shown here demonstrated equally good agreement at pressure levels from 10 to 120 psi.

The data of CENSE 2 provided information to check the elastic calculations for a two-layered clayey-silt soil site. The explosives used were 300-lb spherical TNT charges. In the calculations shown in Figures 3 and 4, the soil was modeled in two layers: a surface layer 20 ft thick with $C_{p2} = 1.1$ ft/msec , $C_{s2} = 0.6$ ft/msec , and $\rho_2 = 1.7$ gm/cm^3 , and a lower half-space with $C_{p3} = 1.6$ ft/msec, $C_{s3} = 0.7$ ft/msec , and $\rho = 1.75$ gm/cm^3 . The measurements were made with velocity gages located 1.5 ft below the surface. Event 2 was detonated with charge center 7.2 ft above the soil surface. Excellent agreement was obtained in Figure 3 at the 67-ft (13-psi) range. There was also similarly good agreement at the 57-ft (16-psi) range. Figure 4 at the 43-ft (34-psi) range shows slightly poorer agreement but still within typical scatter of field measurements. At a range of 32 ft (60 psi) the linear calculations begin to fail to reproduce the major characteristics of the measured motion. The linear theory does not predict the large initial downward and outward displacements seen in the experiments. These differences are probably a result of the nonlinear material properties of the soil becoming important and a result of the close-in source conditions not being adequately modeled by the localized airblast input used in the calculations.

CENSE 3 provided measurements for comparison with theory for a weak soil layer over a hard rock site. This series consisted of seven explosions of 200 lb (226 lb TNT equivalent) of nitromethane. The test bed consisted of compacted backfill of "alluvium" soil placed over a Kayenta sandstone deposit similar to that of CENSE 1. The thickness of the soil was varied from 0 to 6 ft. Measurements of vertical and radial acceleration were made at middepth in the soil layers and in the rock. Velocity histories were obtained by integrating the acceleration records. Events 2 and 4 were surface tangent bursts, that is, the explosive charge was resting on the soil surface. The soil layer thickness in Figure 5 was 6 ft. In Figure 6 the thickness was 3 ft. The material properties used in the calculations were $C_{p2} = 0.9$ ft/msec , $C_{s2} = 0.3$ ft/msec , and $\rho_2 = 1.6$ gm/cm^3 for the soil and $C_{p3} = 8$ ft/msec , $C_{s3} = 3$ ft/msec , and $\rho_3 = 2.4$ gm/cm^3 for the sandstone.

At the 56-ft (12-psi) range of Figure 5 the calculations are in good agreement with the experimental curves up to a time of about 45 msec if the high frequency spikes are neglected. These spikes result from using an airblast pulse with zero rise time. High frequency

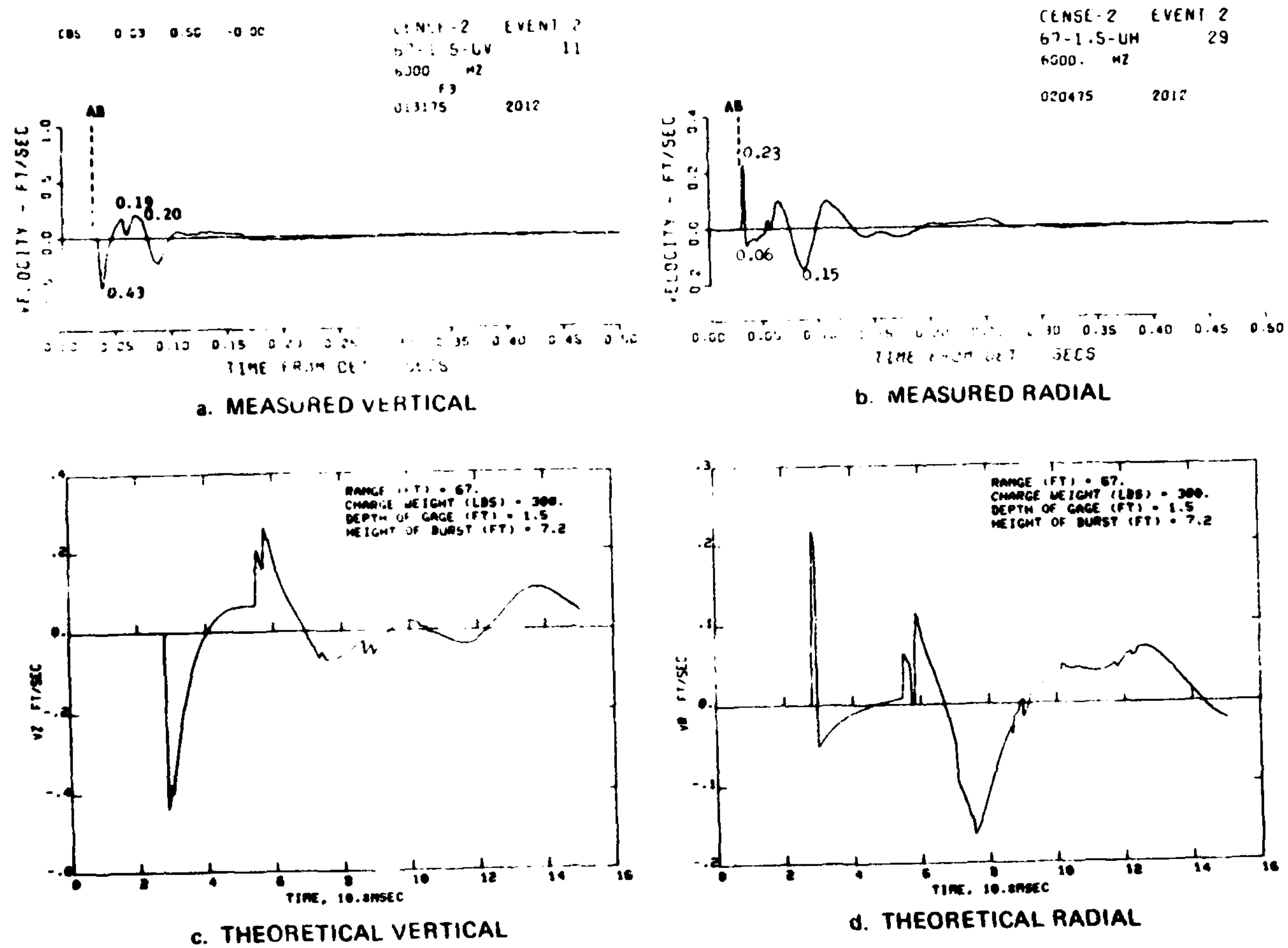


Figure 3. Comparison of particle velocity calculations with CENSE 2 measurements at 67-ft range.

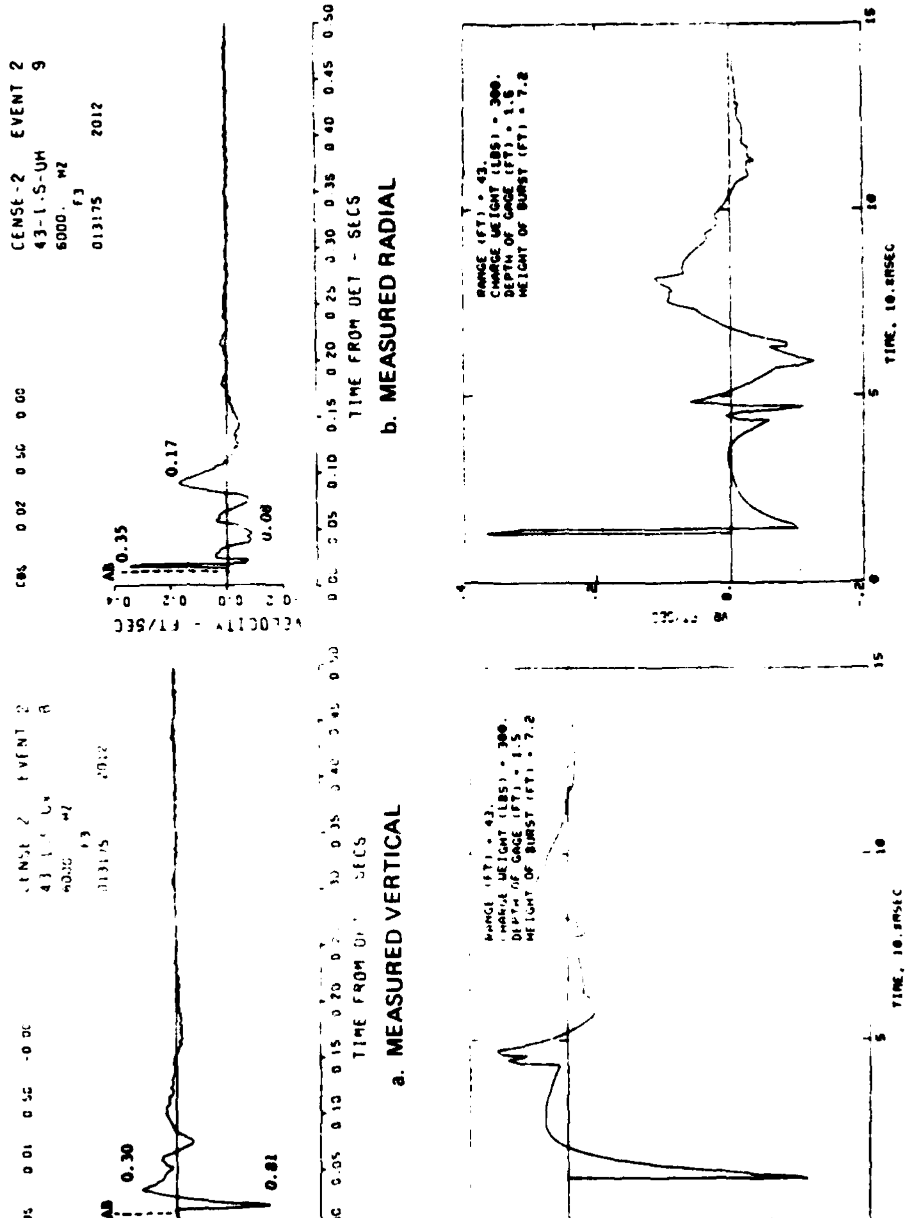


Figure 4. Comparison of particle velocity calculations with CENSE 2 measurements at 43-ft range.

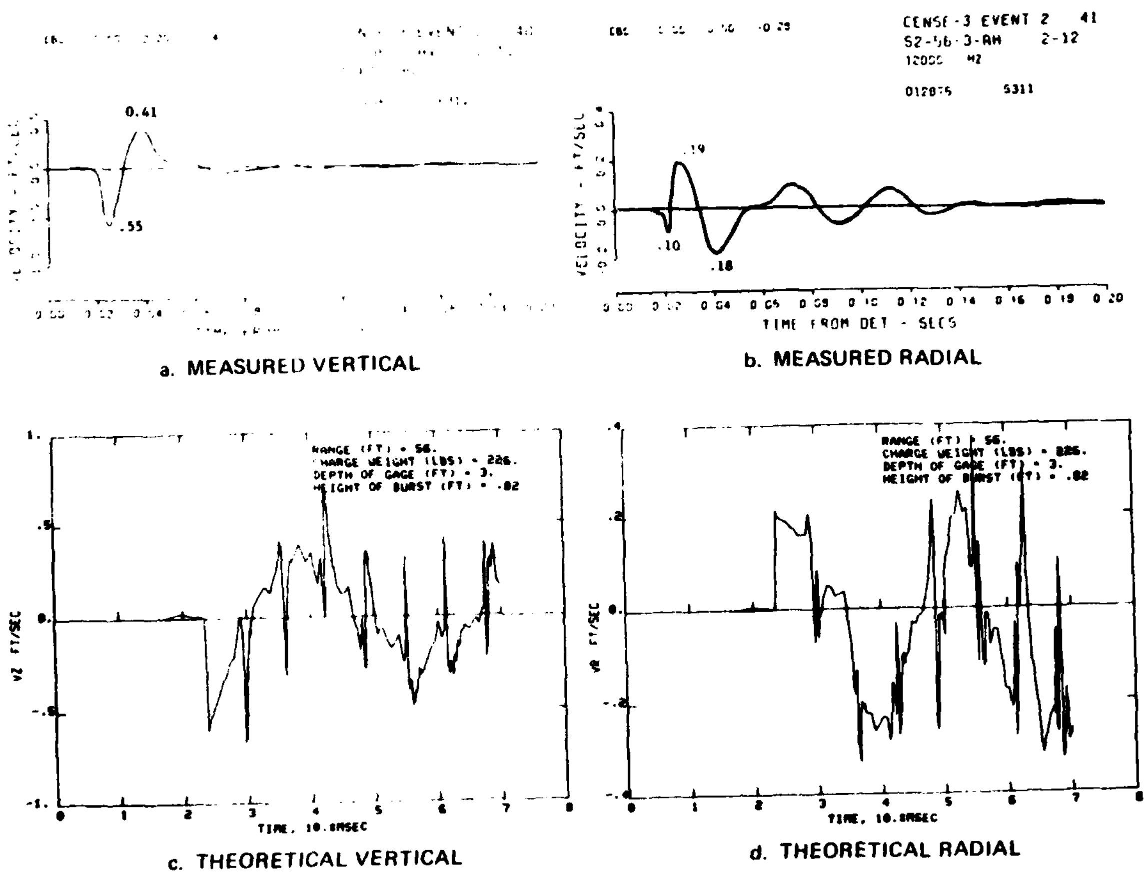


Figure 5. Comparison of particle velocity calculations with CENSE 3 measurements at 56-ft range.

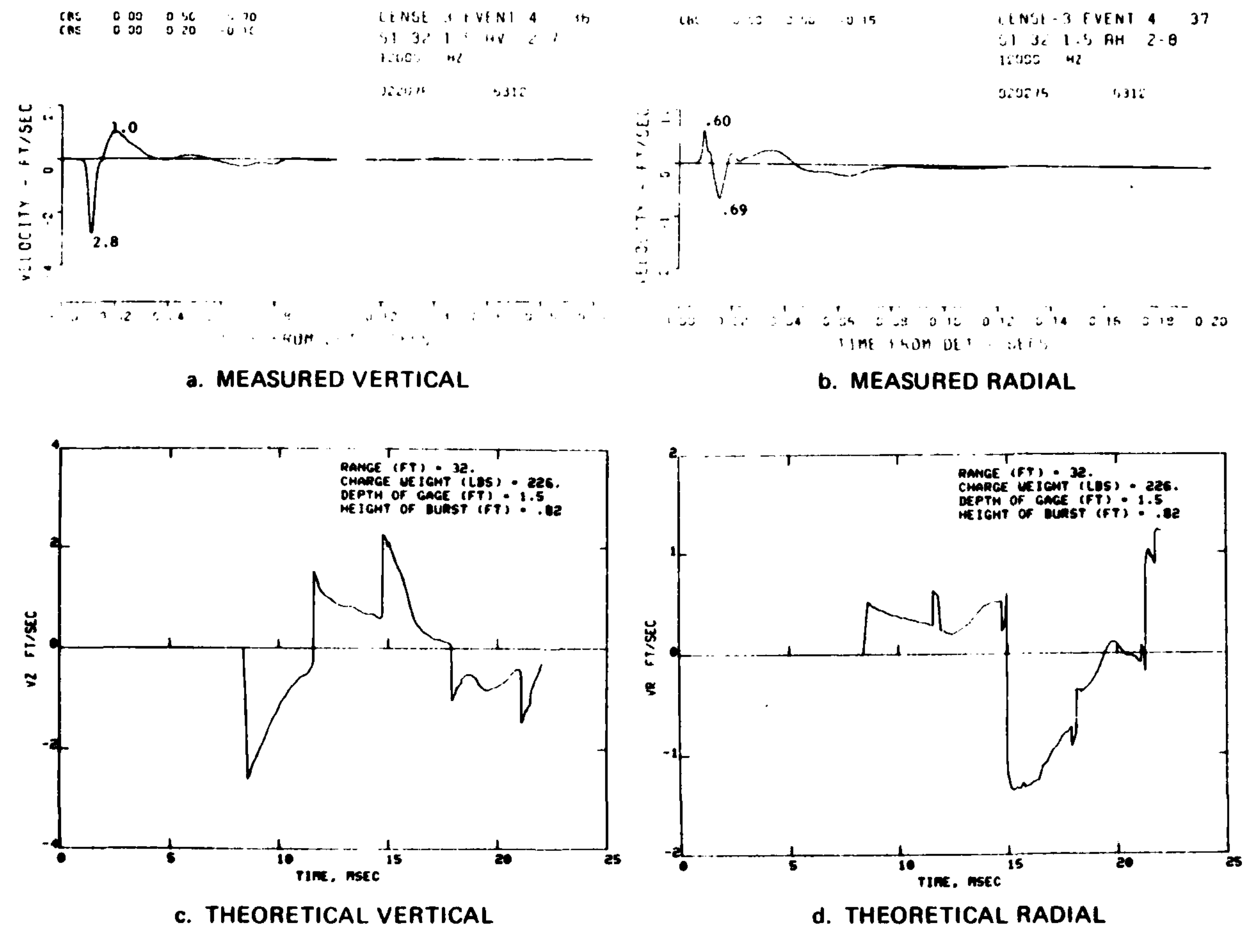


Figure 6. Comparison of particle velocity calculations with CENSE 3 measurements at 32-ft range.

motion of this type is filtered out of the measurements because of the nonlinear effects of the soil and finite frequency response of the gages and recording system. At the 32-ft (52-psi) range of Figure 6, agreement is poorer but the initial velocity amplitudes are still close to the measured values. At a range of 24 ft (110 psi) the calculated initial peaks are nearly a factor or two higher than the experimental.

Figure 7 is presented for comparison with Figure 6 to illustrate the effect of increasing the soil layer thickness at the CENSE 3 site. The initial portions of the records are produced by the directly transmitted P and S waves and are not dependent on the soil thickness. The later motion is a complicated interaction of reflected waves for moderate layer thickness. In going from a layer thickness of 3 ft as in Figure 5 to the 6-ft layer in Figure 6, the change in frequency of the motion is roughly proportional to the layer thickness change, but the waveforms at 12-ft thickness do not follow this pattern.

From the few waveforms presented here, one cannot draw general conclusions on factors affecting the period and amplitude of the low frequency motion. A detailed parameter study and analysis will be necessary to determine how the motion changes in going from very thin to very thick layers. It appears that simple rules of thumb based on S or P wave layer transit times will be valid in only very restricted ranges of thickness and elastic parameters.

4. CONCLUSIONS

Prediction of velocity waveforms using the Cagniard formulation of the elastic theory and the localized airblast source model can be expected to be accurate within the scatter of explosive tests measurements for times up to about one cycle of the low frequency motion and for airblast overpressure levels at the gage range up to about 40 psi for explosions over weak soils and over 100 psi for strong rocks. At pressure levels in the range of 40 to 100 psi for explosions over soil, the elastic theory still predicts the general character of the motion but overestimates the peak velocities and underestimates the large initial downward and outward displacements.

Introduction of a finite rise time in the airblast source pulse is desirable to eliminate high frequency spikes in the calculations. The simple localized airblast source model linearized around the directly transmitted shear wave may be a major contribution to failure of the calculations at higher pressures and at late time on waveforms.

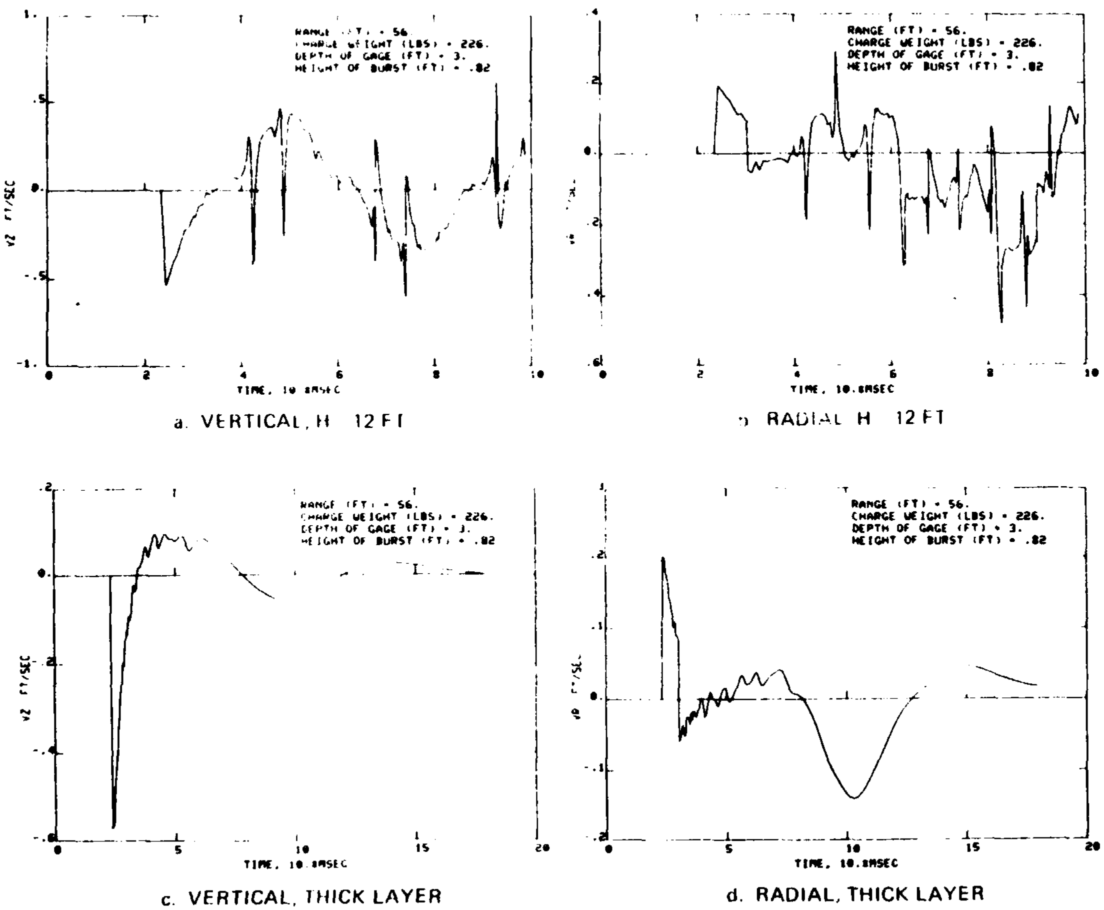


Figure 7. Particle velocity calculations for 12-ft and infinitely thick soil layers.

The linear wave propagation model can produce motion waveforms for homogeneous sites such as the CENSE 1 sandstone at very small computer cost, but because of the rapidly increasing effort required to calculate the late time portion of waveform for layered media, routine calculations to times greater than about three shear wave transit times of the layer appear to be more expensive than linear finite difference methods or normal modes techniques. Calculations with the Cagniard theory for more than two soil layers appear to be quite expensive except for early time motion or special cases where reflections in one layer can be neglected. The primary applications for computing motion waveforms in layered media appear to be early time motions up to about two shear transit times at a relatively low computing cost and minimal effort to change code input parameters. Since the theory follows rays, the composite waveforms can be dissected to study the contributions of individual arrivals. This property of the method makes it ideal for studying the basic characteristics and effects of the controlling parameters of wave propagations in layered media.

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